PARAMETRIC STUDY ON STRUCTURAL WALL–FLAT SLAB CONNECTION UNDER SEISMIC TYPE LOADING

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Abstract

The connection between concrete structural wall and floor slab constitutes a potential weak link in structures resisting lateral forces. The performance of the connection can influence the pattern and distribution of lateral forces among the vertical elements of the structure. For the economical design of a structure subjected to strong ground motion, the structure need to be considered to undergo deformations in the inelastic range. Therefore, in addition to strength requirement, shear wall - slab connections must undergo inelastic deformations without failure. In spite of the significance of the joints in sustaining large deformations and forces during earthquakes, specific detailing guidelines are not explicitly available as codal provisions. By modifying the joint detailing pattern, seismic performance of the connection can be improved to a great extent.

This paper presents the investigations carried out to study the effectiveness of a proposed joint detailing in concrete structural wall-slab connections for the construction of shear wall structures. Numerical investigations were carried out on identical wall-slab joint sub-assembly units with overall dimensions of 2.4m (height) × 0.84m (width): one with conventional reinforcement detailing at the joint and other two with proposed reinforcement detailing at the joint region under lateral seismic type loading. Three-dimensional nonlinear finite element models of the wall-flat slab joint sub-assemblages were developed and analysed using ABAQUS/CAE software. The concrete damage plasticity model was used to model the inelastic behaviour of the concrete material under cyclic loading. As per the results it was observed that the added core shear reinforcement at the joint as the proposed reinforcement detailing for structural wall-flat slab connection exhibited improved ductility in the joint region ensuring increased energy dissipation which is desired under seismic loading.

For carrying out the parametric study, finite element modeling of wall - slab joint sub-assemblages were performed to develop numerical models using ABAQUS/CAE with open stirrups and closed stirrups as core shear reinforcement. The shear capacity was found to be enhanced by 38% for specimen with closed core shear reinforcement when compared with that of the specimen with conventional detailing; whereas the increase for specimen with open stirrups was 32%. A comparison of the Von Mises stress in the joint bars of the specimens indicated an increased stress level in specimen with closed stirrups. The closed stirrups in the core region could take care of the joint shear demands by arresting the tensile forces due to shear by providing increased confinement of the joint core region. The effect of such confinement of concrete core, increased shear taking capacity and better anchorage provides increased overall capacity of the connection.

Keywords: shear wall – flat slab connection; reinforcement detailing; seismic loading; joint shear; ductility

1. Introduction

Of all the natural calamities, earthquakes are probably the most disastrous leading to large scale destruction of lives and property. Many tall reinforced concrete buildings have collapsed under various earthquakes and the reasons attributed were poor design and construction practices. The investigation on the resilience of connections in reinforced concrete structures is of great importance in studying the seismic stability of structures. To analyze and understand the seismic behaviour of concrete structures it requires modeling of geometry, materials and loading. Finite element modelling and analysis will be the best suitable way to include the dynamics in the above parameters. In the literature, the efficacy of prominent software in predicting the dynamic response of structures has already been established [1-6] with much advancement in the field of computational mechanics.

The connection between shear wall and floor slab is an essential link in the lateral load resisting mechanism of wall - slab systems. The performance of the connection can influence the pattern and distribution of lateral forces among the vertical elements of the structure. There exists need for study about simple and proper detailing of connections under seismic loading. By modifying the joint detailing pattern, seismic performance of the connection can be improved to a great extent. In the past decade, considerable research and dissemination of information in the design and detailing of structural elements as well as connections were undertaken. But fewer studies were carried out to address the lack of information on the interaction between floor slabs and shear wall [7-9]. Hence an attempt has been made to understand the behaviour of the connection with the conventional detailing as per British Standards [10] and a proposed non - conventional detailing option in order to provide an integral and better performance of the structural system.

This paper presents the investigations carried out to study the effectiveness of the varied parameters in the proposed joint detailing in concrete structural wall-slab connections for the construction of shear wall structures. Three-dimensional nonlinear finite element models of the wall-flat slab joint sub-assemblages were developed and analysed using ABAQUS/CAE software [11].

2. Wall-slab connection sub-assembly

A six storied R.C. building 12 m x 7.5 m in plan located at Chennai, India (seismic zone III as per IS 1893 (Part 1): 2002 [12]) and founded on medium soil was considered as the prototype building for the study. Figure 1 shows the plan and cross section of the building. The shear wall - slab joint of the first storey (JS) considered for the study is shown in Figure 1. The connection sub-assembly included ground storey shear wall, a portion of the first floor slab and first floor shear wall.

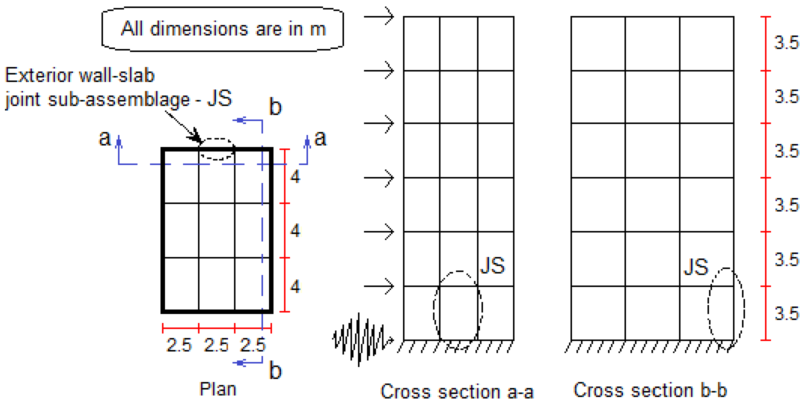

Fig. 1 – Details of the prototype building

2.1 Geometry of wall-slab joint sub-assembly unit

Geometrically scaled down wall-slab joint sub-assembly unit (1/3) was considered for the numerical study. The connection sub-assembly includes a 835x83.5 mm slab connected to a shear wall of 2417x835x100 mm. In order to apply the axial load and out of plane moment, an additional projection of 500 mm was considered at the top of the shear wall. The clear concrete cover thickness was 10 mm and 15 mm for the slab and shear wall respectively. The dimensions and reinforcement details of the sub-assemblage unit are shown in Figure 2 and Figure 3 respectively.

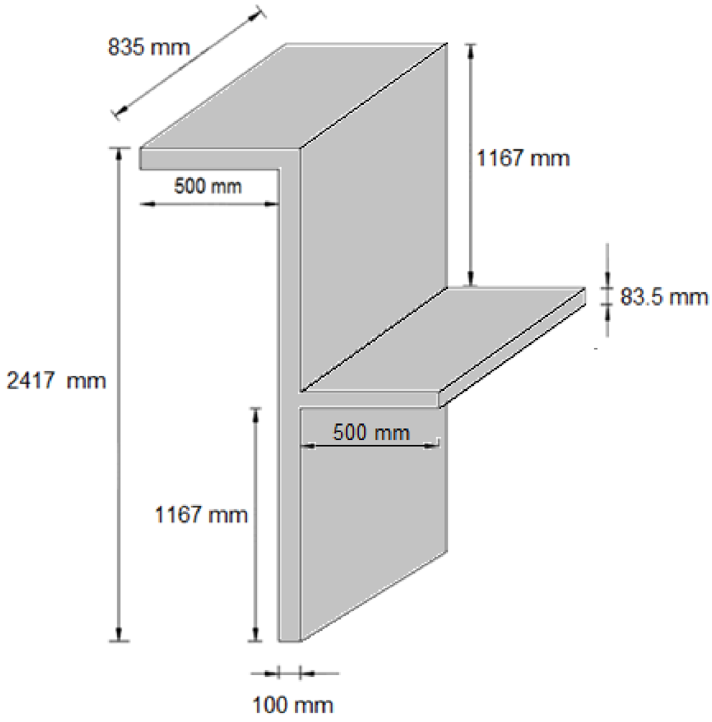

Fig. 2 - Geometry of sub-assembly unit

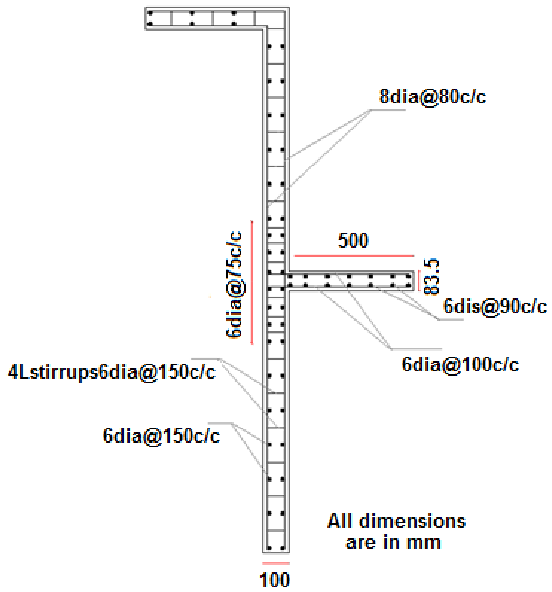

Fig.3 - Reinforcement details of sub-assembly unit

2.2 Connection Detailing of Shear Wall – Slab Joint

The main objective of the study is to investigate the behavior of the wall-slab joint sub-assembly unit with different detailing options under seismic type loading. In the study, the control subassembly unit was constructed with conventional reinforcement detailing at the wall slab joint region, i.e. the provision of U shaped hooks connecting the shear wall and the slab for a lap length equal to development length of the bar (Ld), from the inner side of the wall. The control subassembly unit was designated as 'C type'. While the other subassembly unit designated as 'P type' has been constructed with proposed non-conventional reinforcement detailing, viz. additional core shear reinforcement at the joint region. Wherein, the parameter varied is the type of the additional core shear reinforcement as i) open stirrups and ii) closed stirrups. Hence the wall-slab subassembly unit detailed with open stirrups as the additional core shear reinforcement is designated as 'P1 type' the one with closed stirrups as the additional core shear reinforcement is designated as 'P2 type' units respectively.

3. Finite element modelling

The major challenge in the area of finite element analysis of reinforced concrete structures is the difficulty in characterizing the material properties. Due to complexity of the composite nature of the concrete as a material, simulation of reinforced concrete structures is a challenging task. ABAQUS/CAE [11] has proved to provide solutions for linear, non-linear and explicit problems. The graphical interface of ABAQUS/CAE provides access to define the model with accuracy and is particularly user-friendly in visualizing results.

3.1 Element types – Concrete and Steel

ABAQUS provides Concrete Damage Plasticity (CDP) model which is mainly used for structures subjected to cyclic and dynamic loading. The most significant attribute of damaged plasticity model is its ability to define compression and tension degradation. The damage property lowers the elastic stiffness when the element plasticizes. Therefore, it cannot recover to its initial strength, which is especially important for cyclic loading. The range of degradation is defined by the user.

The behaviour of concrete element under cyclic loading curves represented in Figure 4. The element is subjected to tension exceeding the tensile strength. Crack cause partial damage of the material which can be defined by the parameter d_t and when element is unloaded the modulus to elasticity has changed to $(1\text{-}d_t)E_0$.

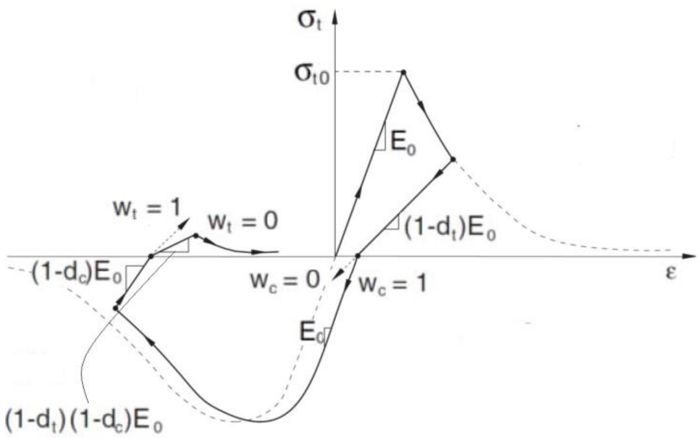

Fig. 4 - CDP model under cyclic loading

If the element is compressed afterwards, its elastic behaviour is determined by the w_c parameter and elasticity modulus in compression is defined as $(1\text{-}d_t\text{+}w_c d_t)E_0$. Assuming that cracks do not influence stiffness in compression, parameter w_c is to be defined as 1. When the value of parameter w_c equals zero (full degradation), the stiffness in compression is identical to the tension stiffness. Crushed section loses its initial properties in compression, defined by parameter d_c, and initial properties in tension, defined by parameter d_t.

Elasticity and plasticity parameters are required in addition to the hardening and stiffening variables to define the yield function for the CDP model. The various CDP input parameters are given in Table. 1.

Table 1 - CDP model parameters

CDP parameters	Input values
Poisson's Ratio	0.2
Young's Modulus (E)	27386.127 N/mm^2
Dilation Angle (ϕ)	38
Initial Biaxial / Uniaxial ratio	1.16
Ratio of second stress invariant on tensile meridian	0.67
Viscosity parameter	0
Flow potential eccentricity (ε)	0.1

The steel reinforcement is modelled as elasto-plastic material. The stress-strain characteristics of the reinforcement steel bars are as shown in Figure 5. In tension it exhibits an initial linear elastic portion, $\sigma_s = E_s \cdot \varepsilon_s$, thereafter a yield plateau at $\sigma_s = f_y$, beyond which the strain increases with little or no change in stress, and a strain-hardening range until rupture occurs at the tensile strength, $\sigma_s = f_{su}$.

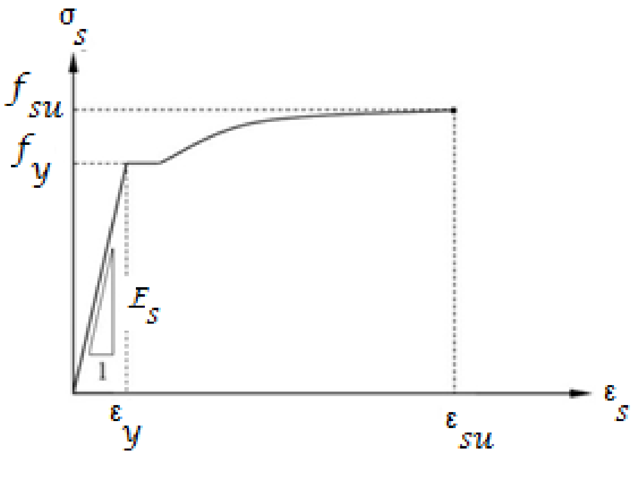

Fig. 5 - Stress strain characteristics of steel

3.2 Modeling of wall-slab joint sub-assembly units

The wall-slab joint sub-assembly units were simulated numerically by means of the nonlinear 3D finite element models. The models were designated as C, P1 and P2, with conventional and proposed type of reinforcement detailing as shown in Figure 6. 3D deformable solid extrusion elements were used for modelling concrete part. For modelling reinforcement steel parts, 3D deformable wire planar elements were used. The compression and tension response input data for M30 concrete enables the calculation of the hardening and stiffening variables by ABAQUS. The compression hardening data and the tension stiffening data were provided in terms of crushing strain and cracking strain respectively for M30 grade concrete. Full bond between concrete and reinforcement was assumed using the embedded region constraint interaction between steel and concrete sections. The embedded constraint is represented in Figure 7. For accuracy, the concrete portion was meshed using with 3D 8-node solid elements (C3D8R, hexagonal eight-node brick) and every reinforcing bar was meshed using beam elements (B31, two-node linear beam) as shown in Figure 8.

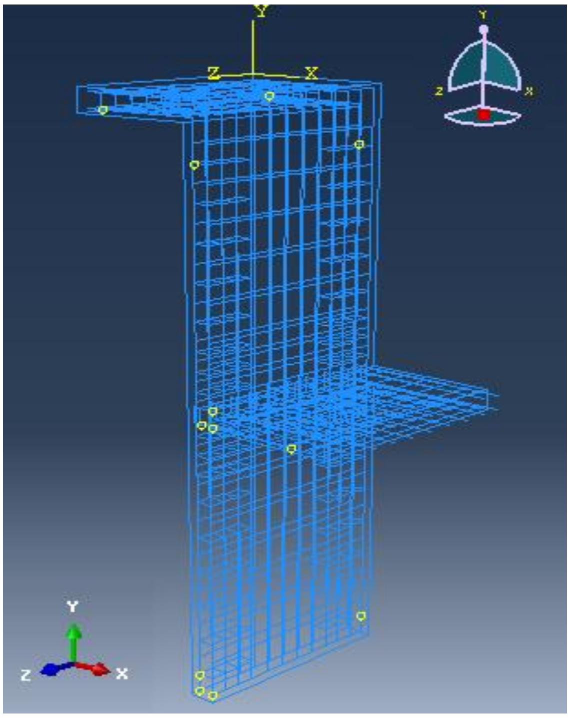

Fig. 6 (a) Model of subassembly unit

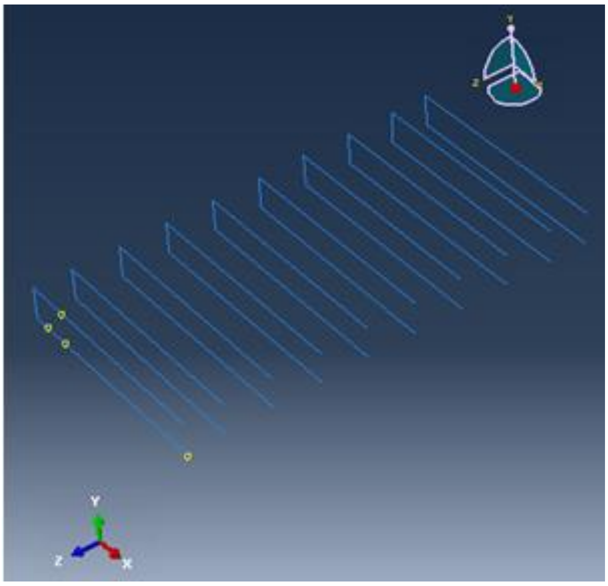

Fig. 6 (b) Modelling of C joint

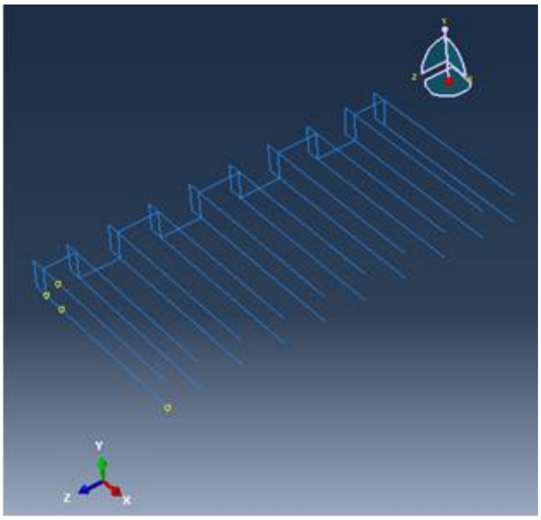

Fig. 6 (c) Modelling of P1 joint

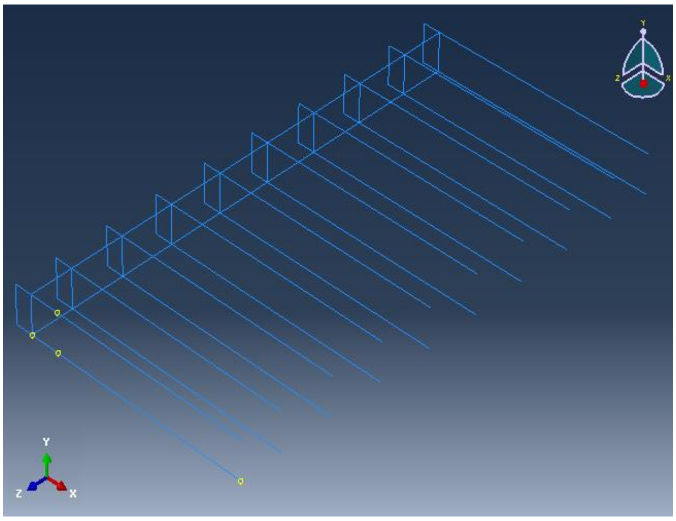

Fig. 6 (d) Modelling of P2 joint

Fig. 6 – Finite element model details.

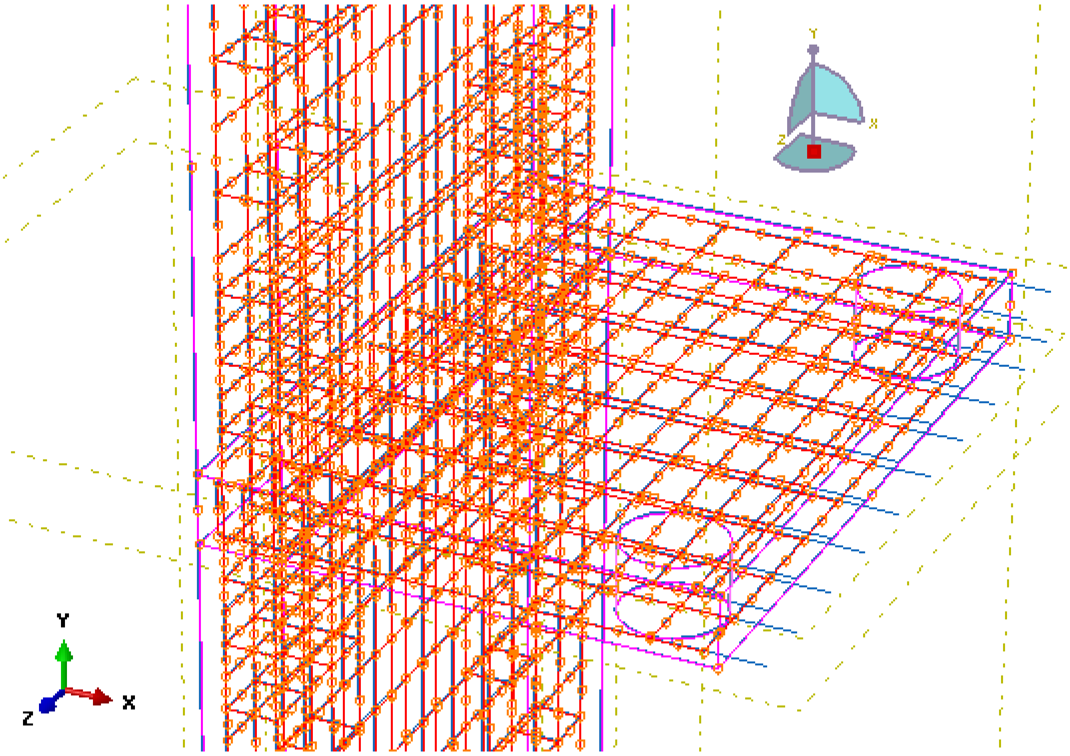

Fig. 7 – Embedded region constraint interaction

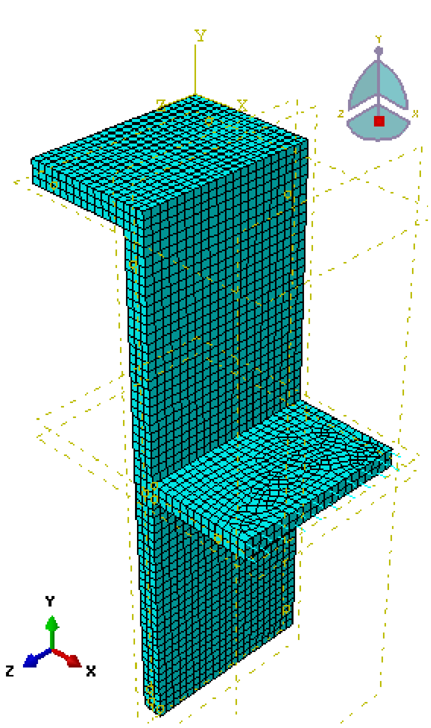

Fig.8 (a) – Meshing of concrete

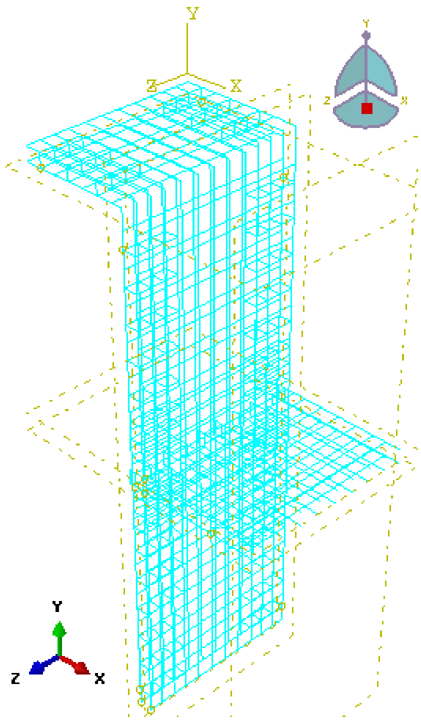

Fig.8 (b) – Meshing of rebars

3.3 Boundary conditions and loading protocol

The shear wall is assumed to be fixed at the base. For this, all degrees of freedom are constrained at the base of the shear wall. At the top of the shear wall, in plane motion is restrained while the out of plane movement due to axial load is allowed. The axial load and the out of plane moment at the top of the subassembly was distributed as pressure at the top slab of the specimen. The loading and boundary conditions of the specimen are shown in Figure 9. The displacement controlled loading was achieved by defining partitions of circular profile and assigning a prescribed displacement to the partitions. The scheduled loading protocol shown in Figure 10 was assigned to the circular partitions. The prescribed displacement cycles were achieved by using smooth step amplitude function. The cyclic loading amplitude was increased in steps of 0.5mm, with three cycles of each displacement amplitude levels; till failure of the specimen.

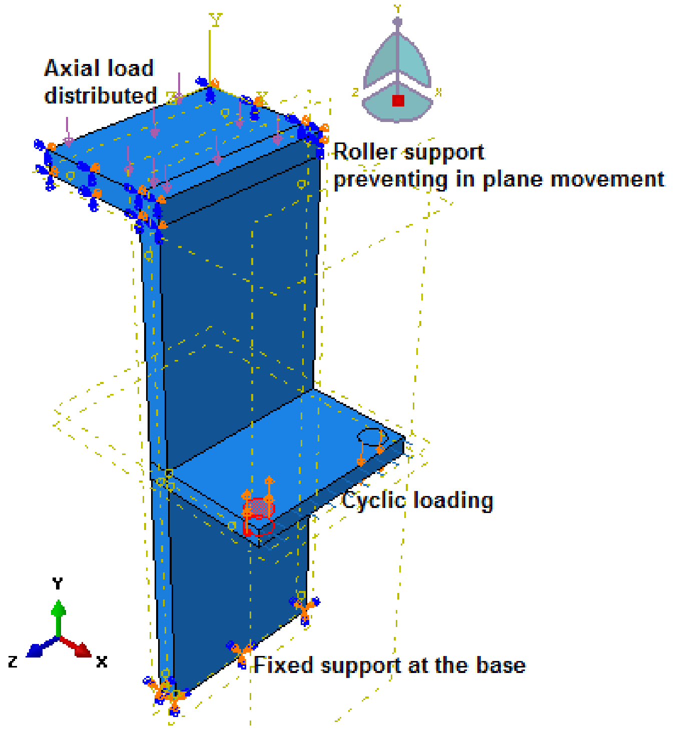

Fig. 9 - Loading and boundary conditions

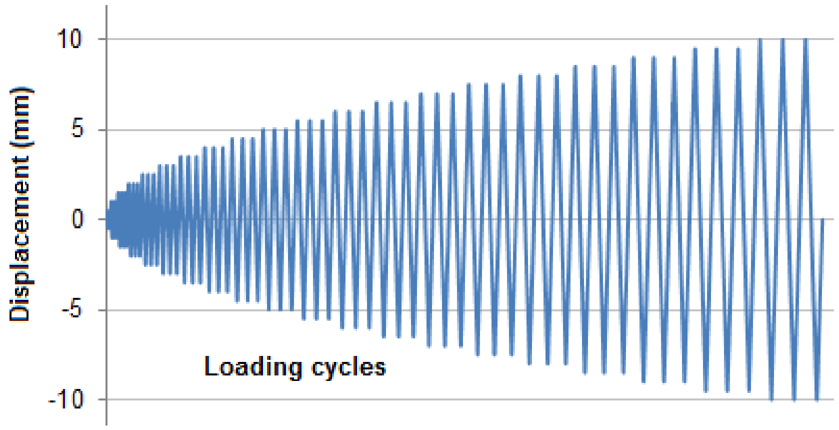

Fig. 10 - Sequence of loading

4. Analysis and Results

For carrying out the parametric study, finite element analysis of wall - slab joint subassembly unit models were carried out. The wall - slab joint subassembly unit models were designated as C, P1 and P2 which were units with conventional U hooks, open stirrups and closed stirrups as additional core shear reinforcement respectively. The analysis was performed in two steps. In the first step the response due to gravity loading has been evaluated and subsequently, in the second step, the response due to cyclic loading has been evaluated. A complete run of the software using one of the available Personal Computers took 20 hours. Inference from the post processing mode showed that the models could predict the capacity and behaviour of the joint sub-assemblage quite effectively. The provision of reinforcement in the core region has been proven to be effective from the computed values under cyclic loading. The observations made from the numerical investigations are presented in the following sections.

The variation in ultimate load and moment carrying capacities for the various categories of detailing for both positive and negative direction of loading is shown in Table 2. The model P1 exhibited 32% and 31% greater load carrying capacity than the conventional C model in the positive and negative direction respectively. Whereas, model P2 exhibited 38% and 37% greater load carrying capacity than the conventional C model in the positive and negative direction respectively. It could be observed that the ultimate load is higher for P2 specimens.

Table 2 - Ultimate load and moment carrying capacity of models

Designation of model	Ultimate Load (kN)		Ultimate Moment (kNm)	
	Positive direction	Negative direction	Positive direction	Negative direction
C	40.6	37.4	20.3	18.7
P1	53.7	49.2	26.8	24.6
P2	55.9	51.2	27.9	25.6

A comparison of the Von Mises stress in the joint bars of the models is shown in Figure 11. An increased stress level was observed in P2 specimen due to the effect of closed stirrups in the core and is resisted within the joint. It was observed that the hooks of the conventional model C at the joint region have got stressed to some extent thereby developing damage at the interface between slab and wall. In the model P2, the closed stirrups have confined the joint core ensuring uniform distribution of stresses into the vertical element bars.

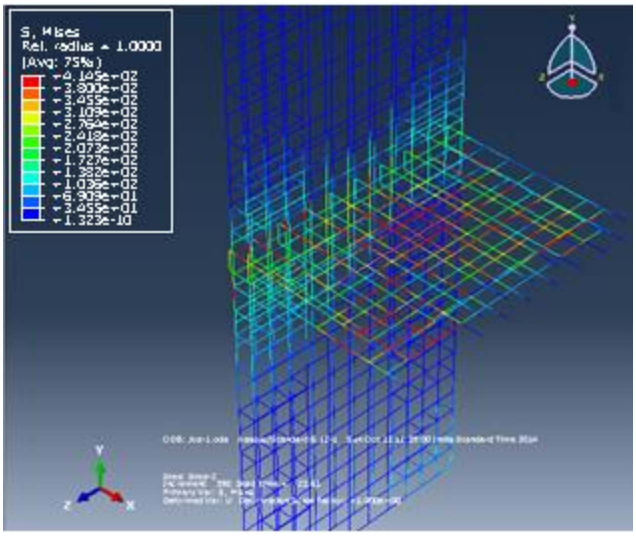

Fig.11 (a) - Von Mises stress at C joint

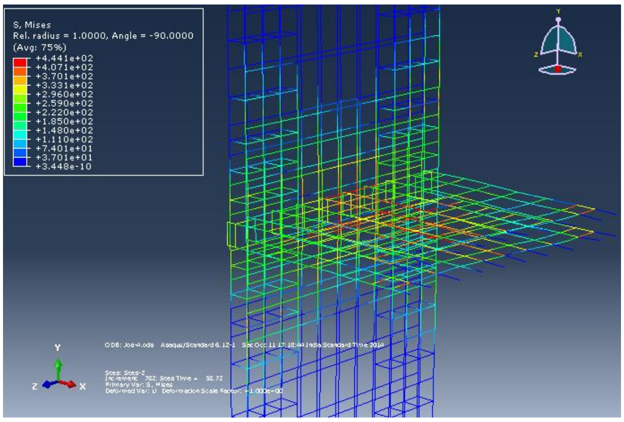

Fig.11 (b) - Von Mises stress at P1 joint

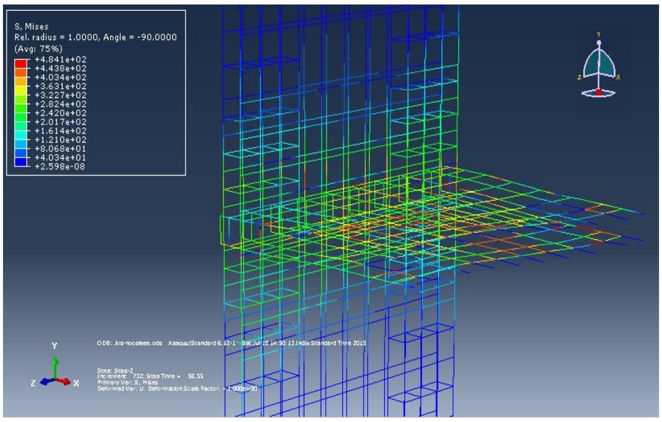

Fig.11 (c) - Von Mises stress at P2 joint

5. Summary and discussion

The detailing of wall to slab connection sub-assembly are expected to cater the joint shear, confinement of concrete, proper construction ability and proper provision of anchorage. However, the provision of additional horizontal U hooks connecting the shear wall and slab meets the above-mentioned expectations, but the void joint core was identified as the part to be modified. For this purpose, modifications were proposed in the joint core by introducing additional core shear reinforcement. Modifications were included by varying the type of core shear reinforcement – viz. open and closed stirrups. Thus, the type of additional core shear reinforcement was identified as the varying parameter in the study.

As per the results, it was observed that the additional shear reinforcement in the core region could take care of the joint shear demands by arresting the tensile forces due to shear. The closed shear reinforcement could also provide increased confinement of the joint core region. The effect of such confinement of concrete core, increased shear taking capacity and better anchorage provides increased overall capacity of the P2 type connection.

6. Conclusions

In this paper, extensive research has been carried out by conducting finite element modelling and analysis to numerically investigate the behaviour of the wall - slab joint subassembly models with and without additional shear reinforcement at the joint core. The study demonstrated that:

- Additional core shear reinforcement can make a significant contribution to the ultimate resistance of the structure. The experimental results showed a significant increase of the slab bending moment.
- The shear capacity was found to be enhanced by 38% for specimen with closed core shear reinforcement when compared with that of the specimen with conventional detailing, whereas the increase for specimen with open stirrups was 32%.
- A comparison of the Von Mises stress in the joint bars of the specimens indicated an increased stress level in specimen with closed stirrups.
- The closed stirrups in the core region could take care of the joint shear demands by arresting the tensile forces due to shear by providing increased confinement of the joint core region.
- The provision of shear reinforcement in the joint core region can be an effective option for detailing exterior wall – slab connection in seismic risk regions.

7. References

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